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16. ABSTRACT

In a wind-tunnel study, the influence of building width and orientation into the wind was examined through concentration profiles in the near wake of the building. The model building was placed in a simulated atmospheric boundary layer. The effects of building width were examined for buildings having width-to-height ratios ranging from 2 to 22. The effects of oblique orientation were examined for angles ranging from -30 to +50 degrees. For most cases, the source was placed midway along the lee side of the building. The stack height was either at ground level of 1.5 times the height of the building. The lateral plume spread from a point source placed near the building was observed to be largest for a width/height ratio of 10. The influence of the end flow around the sides of the building had less effect for wider buildings. For the ground-level source, an oblique angle resulted in a maximum ground level concentration increase by a factor of 2-3 at three building heights downstream. Concentrations were increased by less than a factor or 1.5 at ten building heights downstream. For an elevated source, the building influence on ground-level concentrations was quite similar but with an even larger increase.

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THE INFLUENCE OF BUILDING WIDTH AND ORIENTATION ON PLUME DISPERSION IN THE WAKE OF A BUILDING

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Abstract—In a wind-tunnel study, the influence of building width and orientation into the wind was examined through concentration profiles in the near wake of the building. The model building was placed in a simulated atmospheric boundary layer. The effects of building width were examined for buildings having width-to-height ratios ranging from 2 to 22. The effects of oblique orientation were examined for angles ranging from −30 to +60 deg. For most cases, the source was placed midway along the lee side of the building. The stack height was either at ground level or 1.5 times the height of the building. The lateral plume spread from a point source placed near the center of the building was observed to be largest for a width/height ratio of 10. The influence of the end flow around the sides of the building had less effect for wider buildings. For the ground-level source, an oblique angle resulted in a maximum ground-level concentration increase by a factor of 2–3 at three building heights downstream. Concentrations were increased by less than a factor of 1.5 at ten building heights downstream. For an elevated source, the building influence on ground-level concentrations was quite similar but with an even larger increase.

Key word index: Air pollution, concentration distributions, building downwash, building wake, wind-tunnel modeling, air quality models.

1. INTRODUCTION

Both the oscillations of the wind flow and the enhanced turbulence in the near wake of a building result in enhanced plume dispersion. For a ground-level source, the average ground-level concentrations are thus decreased. However, ground-level concentrations downwind of short stacks are generally increased for short distances near the stack, since the plume is usually brought to the ground nearer the source. Mason and Morton (1987) suggest this is dependent on building shape. The entrained plume near the stack may be less diluted than an unentrained plume would be under normal atmospheric dispersion processes. Ground-level concentrations far downstream converge to the same values whether the building is present or not.

The orientation of the building influences the pattern of wind flow over a building. The orientation also alters the patterns of vortex flow and turbulence initiated in the wake of the building. In addition, the building cross-stream width has an important influence on the flow patterns. This paper reviews some observations of cross-stream profiles of pollutant concentrations in the near wakes of buildings. The effect of building width and orientation is examined to provide an improved understanding and application guidance for estimating pollutant concentrations from short stacks and accidental releases near a building. This wind-tunnel study was conducted at the U.S. Environmental Protection Agency Fluid Modeling Facility.

2. EXPERIMENTAL DESIGN

Detailed features and operational characteristics of the Meteorological Wind Tunnel are described by Snyder (1979). The open-return wind tunnel has a test section 2.1 m high, 3.7 m wide, and 18.3 m long. An Al honeycomb usually spans the cross-section of the entrance to the test section to provide more uniform flow under low tunnel wind speed. The honeycomb was used here, except during the study of the influence of building width. A combination of a 0.15-m fence followed by surface roughness (gravel, approximately 10-mm diameter) was used to produce a 0.8-m deep simulated atmospheric boundary layer in the test section. Figure 1 presents the boundary-layer profiles of the mean velocity, turbulence intensity, and vertical shear stress. The velocity and turbulence data were obtained with constant-temperature hot-wire anemometers in conjunction with an x-array hot-wire probe (end-flow style). The mean velocity at the building height ($H = 0.1$ m) was $3.6\ m\ s^{-1}$. The building Reynolds number, based on the building height as the length scale and the mean velocity at H as a velocity scale, was about 25,000. This exceeds the generally accepted value of about 11,000 for Reynolds-number-independent flow for block-shaped buildings (Snyder, 1981). The ratio of the building height to the depth of the boundary layer was 0.125. For a 1:500 scale model these conditions would correspond to a 50-m-high building in a 400-m-deep boundary layer. The simulated atmospheric flow and turbulence at the surface corresponds to what is usually considered typical over a region of light suburban development (i.e. 20 cm roughness length).

The rectangular block model building had both the height (H) and the along-stream depth (D) equal to 0.1 m. For the study of the effect of cross-stream width (W), W was varied in the range of 0.2–2.2 m. For the study of building orientation, W was fixed at 0.2, 0.4 or 0.8 m. Mean concentration profiles of a hydrocarbon tracer were measured down-

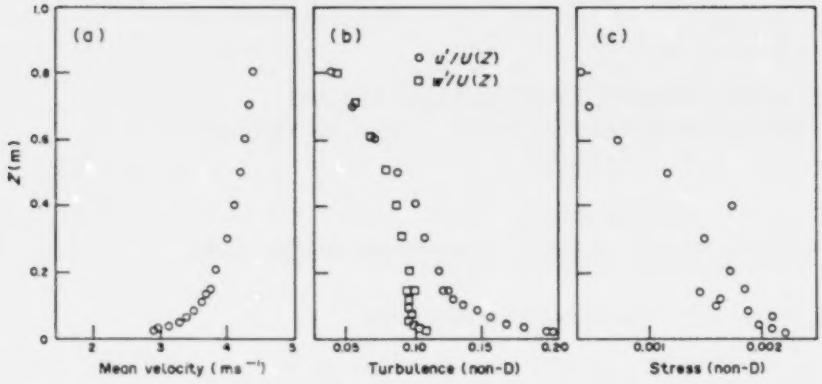

Fig. 1. Vertical profile of (a) mean velocity $U(z)$, (b) along-stream turbulence intensity $u'/U(z)$ and vertical turbulence intensity $w'/U(z)$ and (c) vertical shear stress $-\overline{uw}/U^2(0.8)$

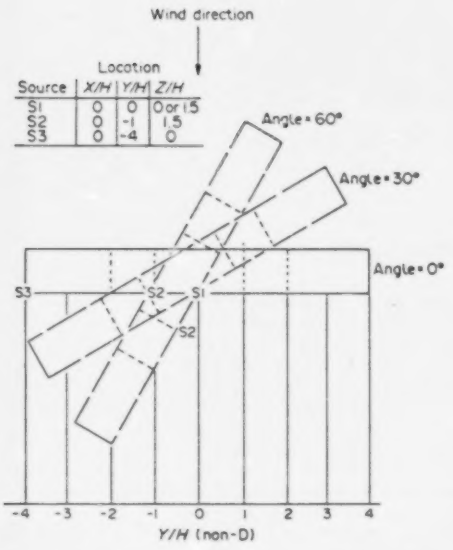

Fig. 2. Plan view of the building and source orientation.

wind from a source placed at the cross-wind building center along the leeward building edge. The neutrally buoyant ethane tracer gas was released through a hollow, perforated plastic, 10-mm-diameter ball. The plume from the source was without plume rise. The source height for these experiments was fixed either at ground level $H_s = 0$ or at 1.5 times the building height ($H_s = 1.5H$). Concentrations were measured with a flame ionization detector that was operated continuously over a sampling period of 120 s. The concentration profiles represent steady-state average concentrations for a fixed wind direction. The observed concentrations (C) are presented in a nondimensional form CUH^2/Q, where U is the meanfree-stream velocity and Q is the tracer emission rate. The free-stream velocity, the building height, and the tracer emission rate were constant among all the cases reported here. These nondimensional concentrations can be linearly rescaled to represent comparable full-scale situations. The discussion presented here relates solely to the observed differences among the different cases; thus, the specific scaling is not a factor.

For these experiments, the building was rotated counterclockwise around the source and fixed at 0, 15, 30, 45 or 60 deg. A few observations were also taken with the building rotated clockwise around the source and fixed at -15 or -30 deg in order to verify the expected symmetry. It is of interest to examine the relationship between the cross-stream profiles of concentration to the projected cross-stream building width. Figure 2 presents a drawing showing the plan view of the building for several angles of rotation. The primary source location is indicated by S1. There were two situations (discussed in section 3.4) in which the source was moved to the corner of the building (S2, S3). For a $W = 2H$ building, the projected cross-wind building dimension W_p ranges from $2H$ for 0 deg rotation to $1.87H$ for 60 deg rotation. Similarly, for $W = 4H$ and $W = 8H$ buildings, W_p ranges from $4H$ to $2.87H$ and from $8H$ to $4.87H$, respectively.

Several parameters of the distributions were used to make comparisons among the cases. The shapes of the concentration profiles were similar. Differences among the concentration maximum, the integrated profile, the standard deviation, and the centroid of the distributions that are discussed in section 3 are significant. Figure 3 presents an example of profiles that were normalized by their maximum concentration.

3. EXPERIMENTAL RESULTS

3.1. *Influence of building width for zero degree orientation*

Ground-level cross-stream profiles and centerline vertical concentration profiles were measured at a distance $x = 10H$ downstream of the ground-level source ($H_s = 0$). Smoke visualization of the flow indicated that the length of the recirculation region ranged from $< 3H$ to $< 7H$ as W/H ranged from 2 to 22. These observations are in agreement with many other reported observations (i.e. Hosker, 1984; Fackrell, 1984). Thus, the profiles should be indicative of the overall initial influence of the recirculating flow near the building. There was additional plume dilution due to enhanced turbulent diffusion downstream of the recirculating flow; this influence would be more sig-

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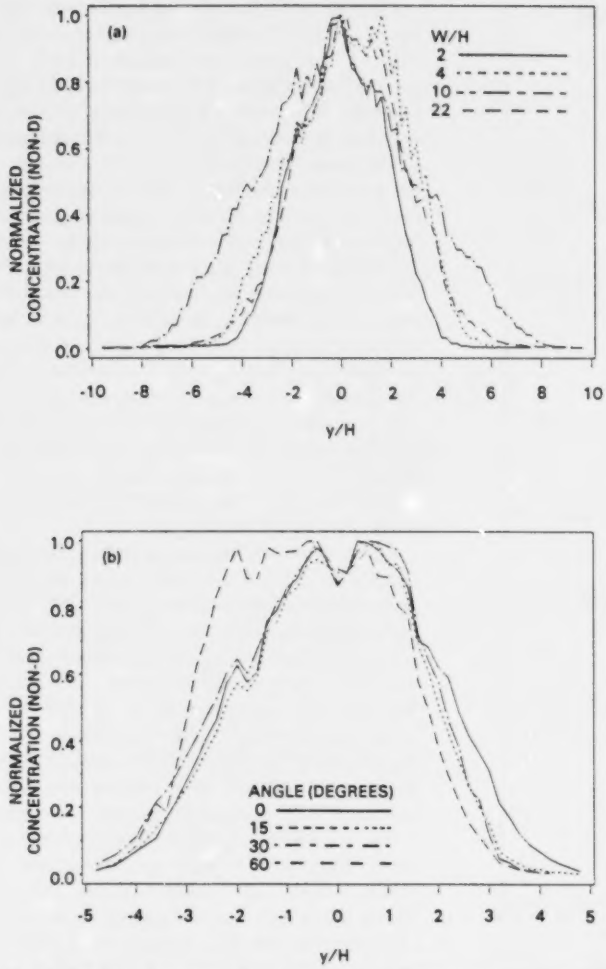

Fig. 3. Profiles of concentration, normalized by the maximum concentration, for S1 ($H_s = 0$) at $x = 10\ H$ as functions of: (a) building width for angle = 0 deg; (b) building orientation for $W/H = 2$.

nificant for the $W/H = 2$ building since the profiles were taken at about $7H$ downstream from the recirculating region, in comparison with the profiles for the $W/H > 10$ buildings taken at about $3H$–$4H$ downstream from the recirculating region.

Some of the characteristics of the profiles are summarized in Fig. 4. The nondimensional integrated concentration is the area under the nondimensional concentration profile (CUH^2/Q vs y/H) which is proportional to the total concentration along a line through the plume. The nondimensional sigma is the spatial standard deviation of the concentration measurements, normalized by H. The vertical spatial standard deviation was calculated assuming symmetry of the distribution about $z = 0$. That is, for a profile with n measurements:

$$\sigma_y = \sum_{i=1}^{n} C_i(y_i - \bar{y})^2 \Big/ \sum_{i=1}^{n} C_i$$

$$\sigma_z = \sum_{i=1}^{n} C_i(z_i - \bar{z})^2 \Big/ \sum_{i=1}^{n} C_i$$

where $\bar{y}$ is centroid of the cross-stream distribution and $\bar{z}$ is set at 0 for the vertical distribution. The shapes of all these profiles were similar. Thus, the ratio of the integrated concentration to the sigma may be considered proportional to an 'average' concentration. The maximum and integrated concentrations were observed to decrease with increased building width for $W/H < 10$. The maximum concentrations from the vertical profiles tend to be less than those from the lateral profiles since the profile may have been slightly

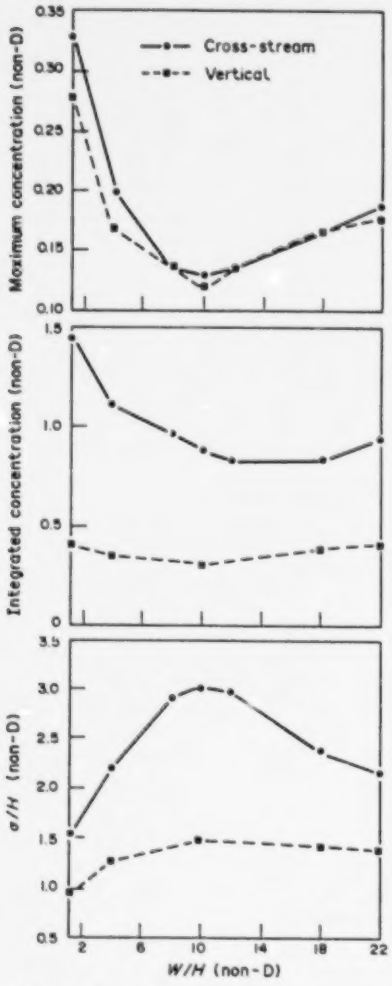

Fig. 4. A summary of characteristics of concentration profiles as functions of building width for S1 ($H_s=0$) at $x=10H$. (Zero-degree orientation.)

off-center due to experimental error in the cross-stream position of the vertical profile. Sigmas were observed to increase with increased building width for $W/H<10$. The vertical plume spread (σ_z) approached its maximum at $W/H=10$ and did not change significantly for a larger building width. The cross-stream plume spread (σ_y) also approached its maximum at $W/H=10$ but decreased for larger building widths. These findings indicate that for $W/H>10$ the flow over and downstream of the building centerline was not significantly influenced by flow around the sides of the building; the influence of the side flow on the entire cross-stream plume was diminishing for $W/H>10$. Evidently, there is a fixed plume pattern for a source far enough away from the ends of a very wide building (i.e. $W/H>20$).

3.2. *The influence of building orientation at* x = 3H

Cross-stream concentration profiles were measured for the $W/H=2$ building at a distance $x=3H$ downwind of the ground-level source ($H_s=0$) and the elevated source ($H_s=1.5H$), respectively. Profiles were taken for each of seven fixed angles at ground level ($z=0$) and an elevated level ($z=1.5H$). Characteristics of the ground-level profiles and the elevated profiles are summarized by Figs 5a and 5b, respectively. In all cases, the pattern for the integrated concentration followed the pattern for the maximum concentration. Therefore, only the latter is discussed here. The observed cross-stream distributions are characterized by their spatial standard deviations (σ_y) and by their centroids (average cross-stream position weighted by concentration), both nondimensionalized by H. For the ground-level source, the shape of all the profiles are symmetric at $z=0$ but skewed at $z=1.5H$. For the elevated source, the shape of the profiles are symmetric at $z=1.5H$ but are skewed at $z=0$. These indicate that the plume is laterally distorted across the lower layer in the building wake.

For the ground-level source, an oblique orientation resulted in a factor of 2 increase in the maximum ground-level concentration at $x=3H$ (Fig. 5a, case 1). Orientation angles near +30 deg resulted in the greatest increase. The σ_y for these oblique orientations was about 75 per cent of that for the 0 deg orientation. The centroid was observed to be slightly shifted toward the downstream edge of the building (see Fig. 2 for reference). The patterns for the elevated profiles for the ground-level source (Fig. 5b, case 1) were observed to be quite different from the gound-level profiles. The 0-deg (perpendicular) orientation resulted in a maximum concentration which was twice that for the oblique orientations around +30 deg. The σ_y for the 60-deg orientation was significantly lower than for all other orientations. The location of the peak concentration (characterized by the centroid) for the increased angle was increasingly skewed in alignment with the side edge of the building that has been rotated in the downwind direction.

For the elevated source the maximum ground-level concentrations (Fig. 5a, case 2) increased only slightly for the oblique orientations. The pattern for σ_y was similar to that for the ground-level source except for being of smaller magnitude. The centroid at $z=0$ was shifted more than for the ground-level source toward the side of the building (as for the elevated profile for the ground-level source). The pattern for the elevated profiles downstream of the elevated source (Fig. 5b, case 2) was different from that of the ground-level profiles. The maximum concentration for the perpendicular orientation was observed to be 2.5 times that for the oblique orientations around +30 deg. The centroid was not influenced by the orientation.

3.3. *The influence of building orientation at* x = 10H

A larger set of profiles was taken at downwind distance $x=10H$. The profiles for $W/H=2$ in com-

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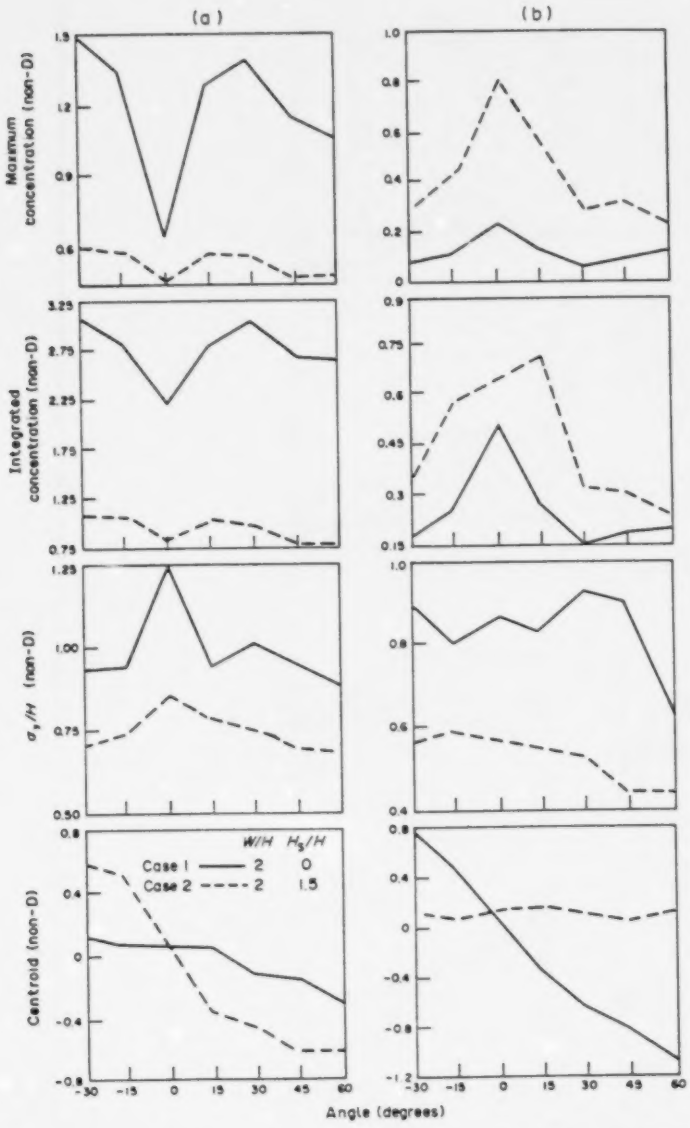

Fig. 5. A summary of characteristics of cross-stream concentration profiles as functions of building orientation for S1 at $x = 3H$: (a) $z = 0$; (b) $z = 1.5H$.

parison with the profiles at $x = 3H$, show an increased plume spread and reduced concentrations; however, the pattern of influence of building orientation was not changed. Figure 6 summarizes the characteristics of the distributions for five groups of profiles. Comparisons among cases 1, 3 and 5 demonstrate the effect of increased building width for the ground-level source. Comparisons between cases 2 and 4 do the same for the elevated source. The concentration measurements at $z = 1.5H$ must be treated with some caution since they could be very sensitive to changes in the height of the plume center.

The concentration maxima represent the plume centerline concentrations at the profile elevation. For both the ground-level source and the elevated source, the influence of angle orientation was similar to that observed at $x = 3H$ for $W/H = 2$. However, the relative differences in magnitudes among the maxima for both the ground-level source compared with the elevated source, and the ground-level profile compared with the elevated profile were diminished, because of added mixing during the increased time of travel. For both the ground-level source and the elevated source, the ground-level concentration maxima decreased as the

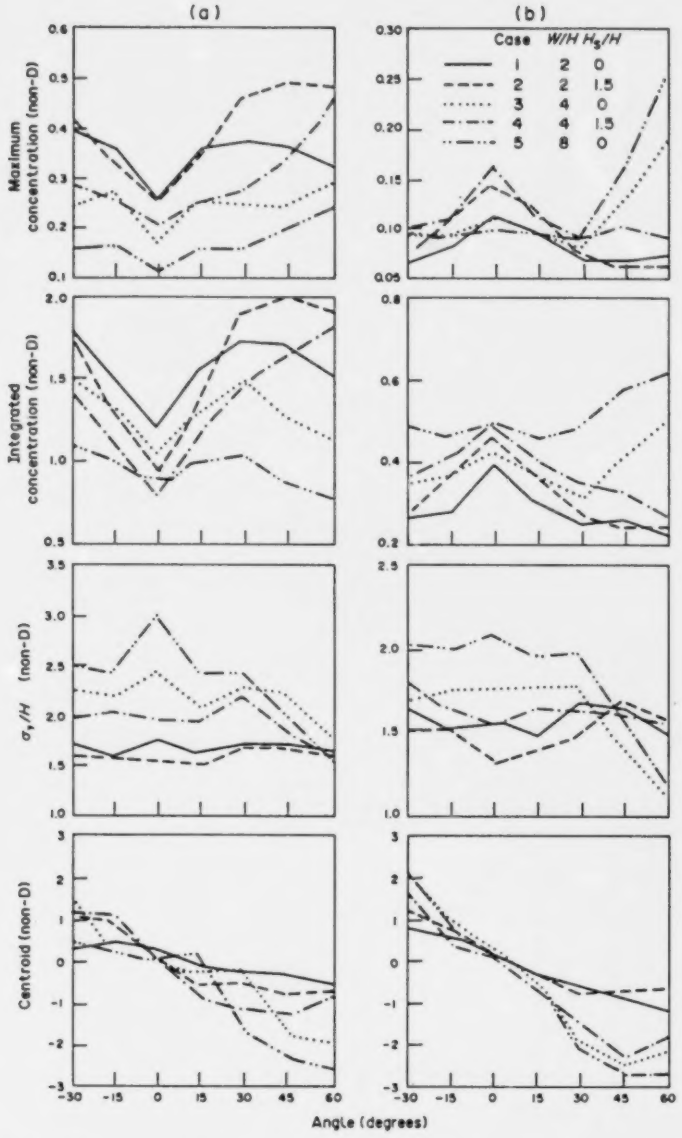

Fig. 6. A summary of characteristics of cross-stream concentration profiles as functions of building orientation for S1 at $x = 10\,H$: (a) $z = 0$; (b) $z = 1.5\,H$.

building width increased. For both sources, the elevated concentration maxima were not affected by increased building width for angles less than or equal to 30 deg. However, for 45-deg and 60-deg angles the maximum concentration increased with the building width. The cross-stream locations of these maxima (closely characterized here by the centroid) were in approximate alignment with the building edge. The wider buildings apparently had a larger vertical mixing depth downwind of the lateral edge. In all cases the centroid was observed to shift toward the downwind edge of the building.

For the wider buildings σ_y was greater, but was significantly reduced for angles > 30 deg. The value for σ_y appears to be somewhat in proportion to the projected downwind dimension of the building. The differences among σ_y for the three buildings at 0-deg to 30-deg orientation angles were proportional to the building width. For the ground-level profiles for both sources σ_y was the same for all cases at a 60-deg orientation angle. For the elevated profiles for the ground-level source, σ_y for the wider buildings at a 60-deg orientation angle was noticeably smaller than for the other cases. The σ_y was observed to be smaller for

the elevated profiles for both sources. The σ_y for the elevated source was both smaller and less affected by orientation angle in comparison with that for the ground-level source.

Differences among the integrated profile values represent differences in the total concentration across the profile. These are not total flux measurements, since transport speeds were not incorporated into the calculations. The values for the integrated concentration nearly follow the pattern of concentration maxima. The only significant difference was in ground-level profiles for the ground-level source. Apparently, for these situations and for large angles, the decreased values for the integrated lateral concentrations can be explained by increased mixing, higher velocity, and/or a plume uplift from the ground. It is possible to have plume uplift from the ground due to vortex flow even though streamlines may be descending above the building.

3.4. *The influence of an off-center location for the source*

Cross-stream concentration profiles were measured for the $W/H=2$ building at distances $x=3H$ and $x=10H$ downwind of the elevated source ($H_s=1.5H$) that was located off-center at $y=-H$ (see S2 in Fig. 2). The building was pivoted around the stack location. These profiles are generally comparable with their S1 counterparts except for the negative angles. Figure 7 summarizes the characteristics of the distributions. The S1 counterpart summaries are presented as case 2 in Figs 5 and 6, respectively. The concentration maxima at $x=3H$, $z=1.5H$ are higher for S2 than for S1, but at $x=3H$, $z=0$ the maxima are lower for S2 than for S1. These results suggest that there was less plume downwash. The σ_y was not much affected by the orientation angle and was somewhat less than for S1. The location of the centroid for S2 was affected by angle much as to that for S1 (except for the -15 deg and -30 deg angles). The values for the integrated concentration follow the pattern for the concentration maxima, as for all other situations.

Figure 8 shows concentration profiles at $x=10H$ for a $W/H=8$ building with a ground-level source at one end (S3 in Fig. 2). In comparison with their counterparts for the S1 ground-level source, these observations indicate the following: For the 0-deg orientation, the plume for S3 was narrower with higher concentrations at ground level and slightly lower concentrations at $z=1.5H$. For the 45-deg orientation, plume profiles for S3 were very similar to those for S1, except that concentrations at $z=1.5H$ were higher for S3. In all cases, the centers of the profiles for S3 were shifted in accordance with the shift in source location.

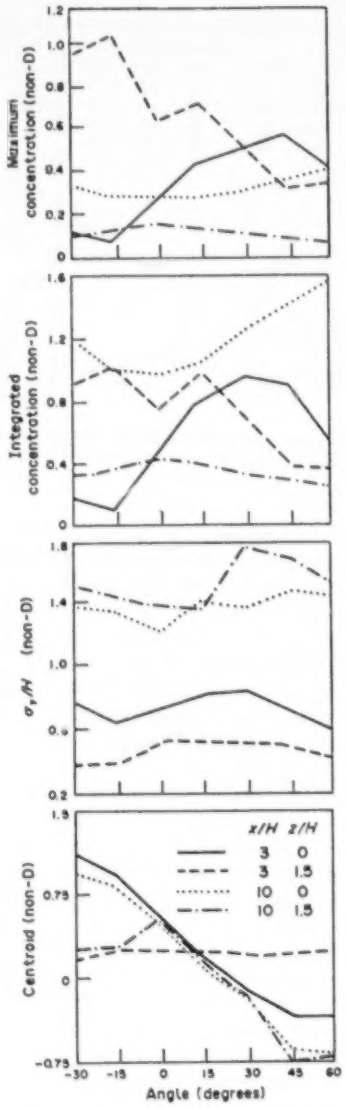

Fig. 7. A summary of characteristics of cross-stream concentration profiles as functions of building orientation for S2 ($H_s=1.5H$).

4. SUMMARY AND CONCLUSIONS

The building orientation can have a significant effect on the maximum ground-level concentrations near a building. For a ground-level source near a building ($W/H=2$) at an oblique orientation angle around 30 deg, maximum ground-level concentrations were increased by a factor of 2–3 at $x=3H$ and by a factor less than 1.5 at $x=10H$. For an elevated source, the building influence on ground-level concentrations was quite similar to that for a surface release, but larger in magnitude. The ground-level concentration was increased by a factor of 2 at 10 H for a 45–60 deg wind orientation angle. The effect of increased building width ($W/H=2$, 4, 8) was to reduce ground-level

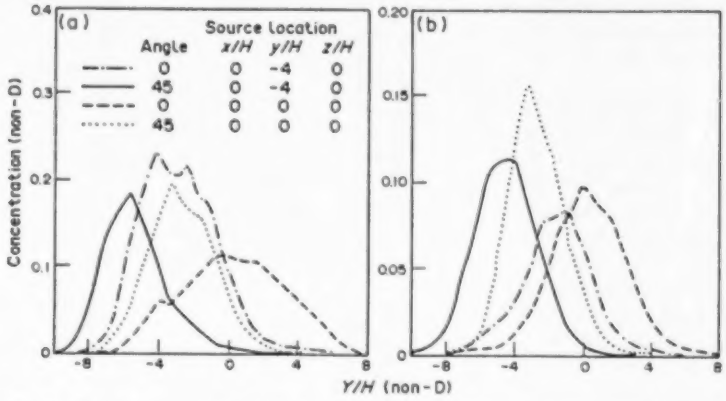

Fig. 8. Cross-stream nondimensional concentration profiles for the ground-level source placed to the side of a wide building ($W/H=8$) at $x=10\,H$: (a) $z=0$; (b) $z=1.5\,H$.

concentrations at all downstream distances, but not in inverse proportion to the increase in width. For a building much wider than $W/H=8$, the influence of the flow around the ends of the building had very little effect on concentrations near the center of the building. For a very wide building ($W/H>20$) the vortices generated by the building end are far from the plume, so the plume from a point source placed near the center of a very wide building normal to the flow looked similar to that for a much narrower building (i.e $W/H=2$ to 4). For a fixed building orientation, a source located off-center of the building shifted the concentration pattern compared to that for a source on center. However, the location of the source did not significantly affect the maximum concentration among the results for all angles.

The pattern of concentrations downwind of the building can be reasonably explained by enhanced turbulence, vortex flow and streamline convergence near the building. A more detailed study of the flow patterns near the building is needed to fully identify and relate them to the concentration patterns. This study shows that, for a low source adjacent to a rectangular-shaped building, the time-averaged plume centerline concentrations may vary up to a factor of 3 because of differences of the angle of wind incidence. The application of these conclusions should be limited to situations with similar building shape, source location, and downstream receptor distance.

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